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STRESS DISTRIBUTION AT THE VERTEX OF A GROWING CRACK

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High-speed motion picture photography is used in combination with the optical polarization method of stress analysis to study the field of elastic stresses at the tip of a crack which is propagating at a rapid rate. It is found that there are a number of singularities of the field which are characteristic only for rapidly propagating cracks and differ considerably from the properties of the field close to a static crack. A "knife," a narrow zone of high tangential stresses, develops in front of a rapidly propagating crack. With a further increase in the rate at which the fracture develops in front of the crack, a zone of isochromatic rings develops in which the tangential stress distribution is identical in various directions from the end of the cracks. The stress in this zone decreases linearly with distance from the end. Branching begins at the moment when different stresses are set up in the zone. The reason for branching is hidden in the very nature of crack growth, in transformation of the stress field at high velocity.

A study of the concluding stage of loading--propagation of a destructive crack--is one of the most important paths toward further development of concepts on the nature of fracture. Considerable difficulties are encountered in the investigation of the kinetics of crack growth, caused chiefly by the extremely rapid rate of crack propagation. This circumstance has resulted in a relatively small number of studies in this field, not at all on a par with the number of works on strength in general and with the experimental requirements demanded by the highly developed theory of this problem. /107*

The fundamental parameters of crack propagation--velocity and acceleration, destructive energy capacity, trajectory of the motion, etc.--are determined by the distribution of stresses at the tip. These stresses have been studied repeatedly in a number of theoretical and experimental works for the case of a static crack (refs. 1-3). The results of these studies are summed up in the conclusion that the stresses in the neighborhood of the crack are an inverse function of the square root of the distance from the tip. It has been found in addition that the maximum stresses are oriented at an angle of 45-60° to the axis of the crack.

Incomparably more important for the problem of fracture is the distribution of stresses around rapidly propagating cracks. Previous studies of this type have been done on metals and polymer materials. Of particular interest in this respect is the work of Wells and Post (ref. 4), where it is shown that the

*Numbers given in margin indicate pagination in original foreign text.

[1] Novokuznetsk.

stresses are identical in the field of a crack for the static and dynamic cases. These data are in patent disagreement with Yoffe's theoretical results (ref. 5), which require variations in the elastic field with an increase in the velocity of cracks propagation, and also contradict the hypotheses of Greggs (ref. 6) and Broberg (ref. 7) on the possible transition to accelerated conditions of crack growth at the former stresses when sufficiently high velocities are reached. We should also point out the work of Akita and Ikeda (ref. 8), where it is shown that there is some difference between the fields of rapidly and slowly propagating cracks.

In our opinion, the conditions of crack propagation should have a fundamental effect on the structure of the elastic field at its tip. This should show up both at velocities far from the branching threshold as well as at the moment when this threshold is reached. The latter case is extremely realistic if only for the fact that the branching process itself can be nothing else but the result of a definite rearrangement in the elastic field at the tip of the crack. Up to the present time, in spite of the existence of a number of works on the observation of branching (refs. 9-11), there has been no investigation or identification of the field at the tip of a branching crack. It has been theoretically shown by G. I. Barenblatt that a singularity in the elastic field in the form of an extended knife in front of the crack and along its axis should be expected even before branching begins at the tip.

The purpose of the present work is to study the field of stresses close to a rapidly running crack and to explain the causes of branching.

Experimental method. The characteristics of the stress field at the tip of a rapidly propagating crack were studied by the optical polarization method. Sheet celluloid 3 mm thick was used as the photosensitive material. The value of a band on the model was σ_0=100 kg/cm^2.

Specimens 50 mm wide were cut from the celluloid sheets and torn on a tensile testing machine at stresses of the order of 500 kg/cm^2. The proportional limit of the material was increased by conducting the tests at 0 to -5°C.

The stresses were determined by the method of observing the bands (ref. 12) in the field of view of a circular polariscope. High-speed still and motion picture photography were used for "freezing" the isochromatics. Unfortunately, this method cannot be used for separating the main stresses σ_1 and σ_2 but gives only the maximum tangential stresses $\tau_{max}=1/2(\sigma_1-\sigma_2)$.

Two series of experiments were conducted. In the first series, photographs were taken of the stress field at the tip of the crack at the moment of growth. High-speed flash photography was used with an ISSh-100-3 tube which has an illumination time of $4\cdot10^{-6}$ sec with a flash energy of 0.8 J. A special circuit was used for setting off the tube (fig. 1), operating as follows: the blades of spark gap SG were fastened to the specimen next to the semicircular concentrator from which the crack originated. Electrical breakdown across the opening of the

crack took place at the moment when the crack passed beneath the blades of SG. A high-voltage electric pulse was sent through delay circuit R_4C_3 to set off tube V. The flash delay time could be regulated by variation of resistor R_4. The isochromatic pattern was photographed as soon as the flash was set off.

Figure 1.

In the second series of experiments, an SFR-2m was used for motion picture photography of the celluloid destruction process in polarized light at 120 and 60,000 frames per second. A special bank of twenty IFK-120 lamps assembled to give uniform luminous flux was used for illumination during photography. The flash energy in this case was 1800 J.

Since the SFR-2m camera is not designed for "slave" operation, it was necessary to use the camera itself for initiating the destruction process. When stresses of about 500 kg/cm^2 were reached (the yield stress of the material), a pulse was sent out by the camera to explode an electrodetonator which applied a blow to the edge of the specimen with a blade 200 mm long. The crack was propagated from the point of the blow. The flash was synchronized with the moment when fracture was started either by direct connection through a contact device fastened to the blade or by an electronic circuit, to delay the original pulse by the time necessary for development of the explosion in the detonator ($200 \cdot 10^{-6}$ sec).

The objective lens mount of the SFR-2m camera was somewhat modified to produce an image of satisfactory quality with exposure from a distance of 70 cm.

Experimental results and discussion. 1. As is generally known, the phenomenon of brittle fracture is accompanied in all cases without exception by plastic deformation of the material in the zone immediately adjacent to the crack. This characteristic must be considered when analyzing any destruction process. From this standpoint, the material used in this study is similar to metals, since crack propagation in this material is associated with a plastic zone which is easily visible on a number of photographs (fig. 2). The opaque black edge bordering the crack is deformed celluloid. According to our data, the length of the plastic zone in front of the crack may reach 8 mm. According to reference 13, the effective size of the crack is greater than the actual size by the magnitude of the deformed zone in the case of a quasi-brittle fracture, and the boundary of this zone should be taken as the area of the crack. The material beyond the effective crack is in the elastically stressed state. This may be explained by the fact that the isochromatic rings which determine the elastic field of the specimen begin in front of the plastic region in our case. Rings of this type going out in front and to the sides of the crack line have been quite thoroughly studied, e.g., in reference 4, and we will give them no further consideration. Particular attention is drawn to the distribution of

Figure 2.

stresses on the prolongation of a running crack since the behavior of the destruction process, its velocity, and the question of whether the crack is single or branching, are determined by the behavior of the material in this particular zone.

Photographs of the stress field at the tip of a running crack were taken by high-speed isolated flash exposure. These photographs may be seen in figure 3a and 3b. Attention is drawn to the fact that there is a bright narrow band up to 15 mm long and about 2 mm wide in front of the crack. There are three hypothe- /109
ses which may be given to explain the nature of this band: (1) the band developed as a result of plastic deformation of the material; (2) the band is a zone of "silver" cracks (ref. 14); (3) the band is an isochromatic with a fractional number. The first hypothesis must be rejected since, as was shown above, the opacity of the plastic zone makes it easy to pick out on photographs. We have repeatedly observed that celluloid becomes less transparent with any plastic deformation. It must be said with respect to the second hypothesis that "silver" cracks should also look black in transmitted light (see, for example, reference 14).

Thus the band is an isochromatic "knife" of stresses (fig. 4a). The

stresses in this "knife" reach 150 kg/cm^2 (according to the band method). This form of the elastic field is characteristic only for a rapid destruction process. It was established by motion picture photography (60,000 frames per second) that the "knife" appears at a crack growth rate of about 300 m/sec. Figure 3c is a photograph of the stress field near a static crack produced under these conditions. As was correctly pointed out in reference 4, there is little difference between the stress distribution in the static case and that in the dynamic case, although there is no "knifelike" isochromatic associated with a stationary

crack.[1]

It may be assumed that this characteristic of the elastic stress field close to a rapidly propagating crack plays a considerable part in the destruction

[1]It should be pointed out that a "knife" similar to that described may be seen in the photographs in references 4 and 15.

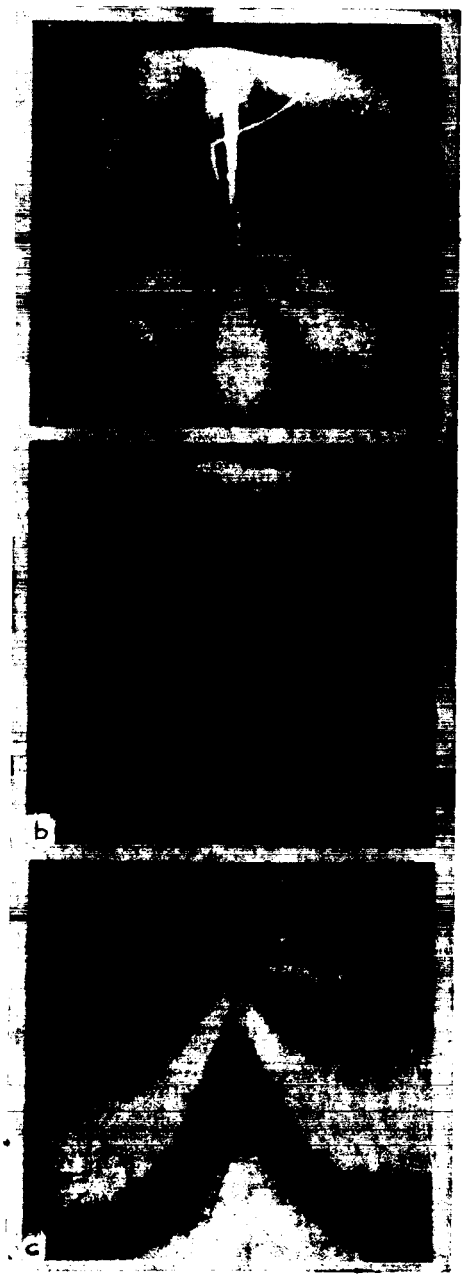

Figure 3.

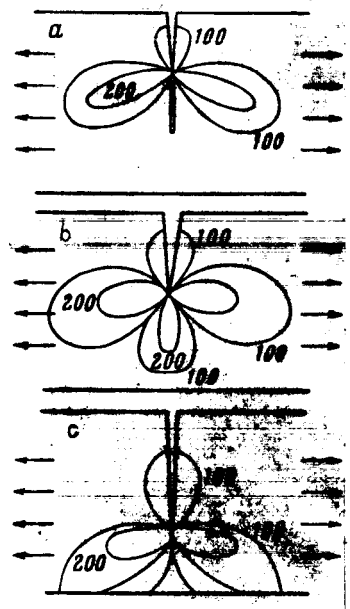

Figure 4.

process. In a zone as narrow as our "knife," deformation energy is concentrated and the yield stress is reached earlier, facilitating the formation of microscopic cracks.

2. A different pattern is observed in the stress field near a crack running at a velocity /110

close to the maximum possible.[1] Motion picture photography (120,000 frames per second) was used to determine the stress distribution in the case of fracture development at a rate of 500 m/sec. Photographs of this process are shown in figure 5. The "knife" discussed above is not formed at this high velocity. In this case, a zone of isochromatic rings develops in front of the end of the effective crack, moving together with it. The outer boundaries of this region are inclined at an angle of 45° to the line of continuation of the crack. The linear dimensions of this zone reach 30 mm. Figure 4 b shows the arrangement of the isochromatics at the end of a rapidly propagating crack. It was even possible to determine the stresses in the ring zone. These stresses decrease linearly with distance from the end of the crack (fig. 6).

Similar distribution of the isochromatics in front of the tip of a crack was found analytically by Baker (ref. 16). According to his calculations, this type of distribution is characteristic for crack propagation at a velocity close to the maximum possible (the speed of Rayleigh waves in the given material). In the given case, development of isochromatic rings takes place at a

[1] Increase in crack growth rate was attained at -5°C.

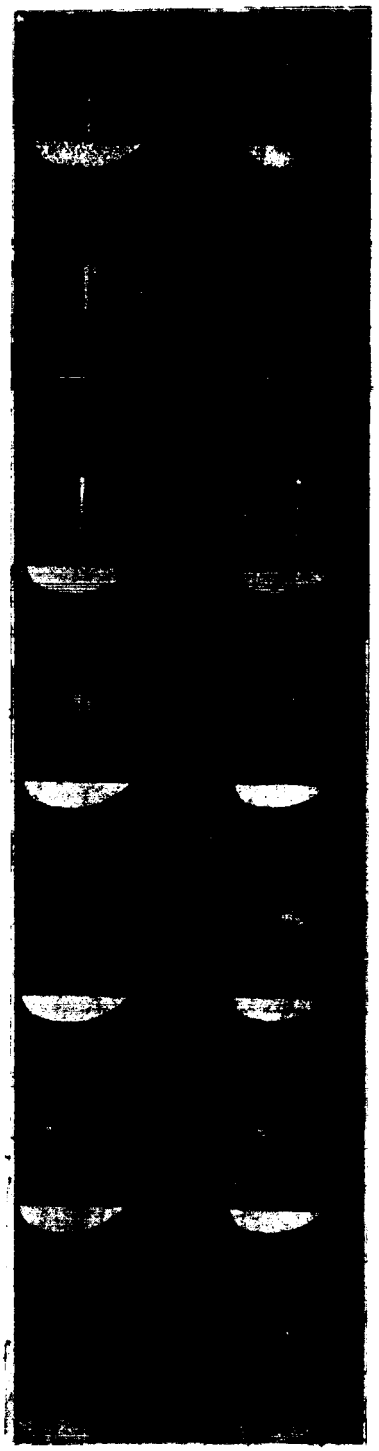

Figure 5.

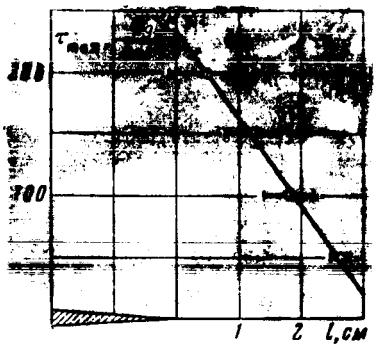

Figure 6.

Figure 7.

rate of the order of 0.9 times the Rayleigh speed for celluloid, i.e., under the conditions found by Baker.

Intense branching of the crack took place characteristically in all cases where isochromatic rings were observed, usually beginning at the moment when the crack had traversed 1/5 the diameter of the specimen. The typical form of a fractured celluloid plate is shown in figure 7.

There is a possible relationship between the branching of a rapidly running crack and the given singularities of the field of elastic stresses in its neighborhood. The isochromatic rings outline a section in front of the fracture zone where the distribution of stresses is the same on both the continuation of the crack and in directions inclined to this continuation by an angle of 45°. This type of stress distribution makes straight-line propagation of the crack and lateral deflections equally probable. A similar result for a rapidly propagating crack was analytically obtained by Yoffe (ref. 5), but the existence of a zone of differing stresses had not been previously observed experimentally.

Thus the cause for branching of a rapidly running crack is hidden in the very nature of its growth, in the form of the elastic stress field surrounding the fracture zone.

There is still another view on the nature of branching. It is assumed that the crack branches as a result of interaction between the stress field at its tip and elastic pulses reflected from the edges of the specimen (ref. 9). Undoubtedly this type of interaction can bend the trajectory of the crack and cause branching, but this phenomenon alone cannot explain all the observed relationships. It may be seen in figure 5 that the edge of the specimen has an effect on the elastic field only when the tip of the crack is close (of the order of 1 cm) to this edge (see diagram in figure 4c). This effect may be summed up as follows: when the outer isochromatic ring reaches the edge, the inner isochromatic is reduced in width and transformed into a "knife" similar to that described above. The crack begins to branch long before this type of bending takes place.

Besides, if reflected impulses were the sole cause of branching, the position of the first branching point in this case would depend on the width of the specimen. We conducted control experiments on fracture of specimens varying in width made from polymethylmethacrylate (a material which shows excellent branching). The width of the specimen had no observable effect.

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